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Further upgrades of the 10 micron interferometer have been made during 1998, tested, and used. The present system now provides improved tracking, stronger signals, and more precise infrared measurements. A number of stars have been measured. Some are newly measured, others are remeasured and show changes. Narrow band filters have been installed and used for interferometry on spectral lines.

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Annual Technical Report on ONR Grant N00014-96-1-0737

for the Support of Infrared Spatial Interferometry

Introduction

The grant N00014-96-1-0737 began March 1, 1996. Its purpose is to develop infrared interferometry and to explore high precision astrometry in the 10 micron wavelength region by interferometric techniques. This involves study and measurement of atmospheric properties as well as development and testing of advanced interferometric equipment. The work is being carried out with the help of two 65 inch telescopes, stationed at the Mount Wilson Observatory, which can be separated by various baselines, and which contain HeNe laser interferometers to measure pathlength distance fluctuations near the ground. We report here the results of work during 1998.

Recent Technical Improvements

A number of changes and improvements which have been summarized in our 1997 report were made in our interferometer during 1996 and 1997. They have enhanced our ability to measure the visibility and track the phase of stellar interference fringes. Improvements include computer upgrades and substantial reprogramming of the operating programs, new tracking cameras for both telescopes which are sensitive to 2 micron infrared radiation, their programming to automatically track stars, and installation and testing of a tip-tilt system for fast correction of stellar motions due to seeing fluctuations. Another substantial improvement has been made in 1998, which allows more accurate measurements of infrared intensities by eliminating a problem which has heretofore troubled all IR heterodyne detection. This is described below.

Detection of mid infrared signals against a background of room temperature radiation usually requires the signal to be chopped. In the case of heterodyne detection, a very small fraction of the local oscillator power striking the detector will inevitably be scattered towards the chopper, then scattered back towards the detector. This small amount of radiation is itself chopped, and hence produces a spurious signal in a lock-in amplifier arranged to detect the chopped frequency. Because the spurious signal, of electric field intensity E_s, is coherent with the local oscillator of electric field E_o, it produces a spurious power heterodyne signal proportional to $(E_o + E_s\cos\theta)^2 - E_o^{\,2}\cos\theta = 2E_oE_s$, where θ is the phase angle between E_s and E_o. This power can be very much larger than scattered power itself, which is proportioned to $E_s^{\,2}$. For example, a fraction 10^{-10} of a local oscillator power of a milliwatt backscattered in this way produces a signal about 2×10^{-8} watts. This is much larger than normal random noise. Such a signal also varies with time, because small temperature or mechanical changes can change θ, the relative phase of E_s and E_o.

This false signal can, however, be compensated. The backscattered radiation produces a signal in the detector current, and varies this current as the relative phase and signal changes. The varying current, because of the coherence of the scattered wave, changes relatively slowly, at acoustic frequencies rather than at frequencies in the megahertz and gigahertz range where stellar radiation is being detected. Hence, the varying detector current can be used to quite precisely cancel the varying spurious signal.

We have shown that the resulting spurious signals can be cancelled to less than 1% of their value, and rather simple circuit changes in our detection system are in operation which as a result have enormously improved our precision in measurement of infrared intensity.

The technique described here provides a simple and rather complete cancellation of spurious signal due to backscatter in heterodyne detection, and we believe should be useful in other systems as well as in our own work. A more complete technical discussion is given in Appendix 1.

We have realuminized our four large mirrors this year, and this has improved their reflectivity. We are also now regularly using CO_2 snow to remove dust, and this seems quite effective. Representatives from other observatories have come to us to become acquainted with CO_2 snow techniques, and are now using them.

We have also installed frequency filters in our r.f. circuits so that interferometry can be done in a narrow band of wavelengths, and hence carried out on spectral absorption or emission lines. Work of this type has now been done as part of the thesis of one of our students, John Monnier. It gives somewhat surprising results, which we are in the process of analyzing.

Illustrations of Recent Measurements and Results

A number of new measurements on stars have been completed during 1998. Many of these remain to be written up for publication. In the meantime, this year many of our earlier results have been published, as can be seen from the list of publications. This year's results are substantially assisted by the technical improvements made during the last two years, and also by independent measurements of visibility of some of the same stars at near infrared wavelengths. We have made the latter measurements using a multiple-hole mask over the Keck telescope. The Keck telescope has a diameter of 10 meters, so baselines obtained by this method are limited to

10 meters. This gives adequate resolution for near infrared wavelengths, but will not be as rewarding in the mid infrared. However, some members of our group have been perfecting a 10 micron infrared camera for the Keck telescope, and pictures taken with it, using the full aperture of the 10 meter telescope, should be very useful when combined with our interferometry on Mount Wilson, which can provide higher resolution.

One of the interesting stellar results obtained recently is shown in Figure 1. This shows a change in the visibility curve for the star NML Cygni between our earlier measurements in 1994 and those in 1998. These changes are most obvious at the higher resolution part of the curve, near spatial frequencies of $6-8\times10^5$ cycles per radian. This figure also illustrates the improved precision of our measurements as a result of recent technical upgrades, as is seen in the large difference in probable errors for points on the curve taken at the two different times. The difference is most evident at the higher resolutions, in the range of $6-8\times10^5 rad^{-1}$ in spatial frequency.

Another illustration of results which have been improved by recent technical upgrades is given in Figure 2. This shows the visibility curve of IRC+10011, a star which was too dim to track with our previous camera equipment. Installation of a sensitive infrared camera now allows much improved tracking of many stars.

Results on IRC+10011 and another star, IRC+10420 are published in the thesis of one our students, Everett Lipman and are being written up for journal publication.

Plans for the Coming Year

Along with plans for continued extensive stellar observations and further system improvements, we had expected this year to set up one tall pole for precision measurement of small and local temperature fluctuations as a function of height above our observing position, and thus to examine correlations between such fluctuations and the observed seeing. We have done some work in this direction, but have not yet installed such a pole. We plan to do that in the coming year. This year we have studied types of poles and temperature detectors which would be suitable, and made test measurements of detector response to check both sensitivity and the rapidity of response. We have found some quite satisfactory detectors, and plan substantial measurements with them in the future. Their responsivity is illustrated by Figure 3, showing signals from three detectors, each a few feet apart, which provide rapid measurements of local atmospheric temperatures. We also have made a proposal to the Army Research Office to finance the acquisition and use of two additional poles for detailed air temperature fluctuation measurements. This should be useful by allowing us to study correlations of atmospheric fluctuations at more than one location and near more than one telescope.

Publications during 1998

W.C. Danchi, B. Lopez, M. Bester, E.A. Lipman, J.D. Monnier, P.G. Tuthill, and C.H. Townes, "Secular variations and non-spherical structures in the dust shell of o Ceti observed with a long baseline interferometer at 11 μm," in *A Half Center of Stellar Pulsation Interpretations: A Tribute to A.N. Cox, ASP Conference Series* Vol. 135, eds. P.A. Bradley and J.A. Guzik, ASP Press, p. 327 (1998).

Peter Tuthill, John Monnier, William Danchi, and Chris Haniff, "Morphologies of dusty circumstellar envelopes," in *A Half Center of Stellar Pulsation Interpretations: A Tribute to A.N. Cox, ASP Conference Series* Vol. 135, eds. P.A. Bradley and J.A. Guzik, ASP Press, p. 322 (1998).

J.D. Monnier, M. Bester, W.C. Danchi, M.A. Johnson, E.A. Lipman, C.H. Townes, P.G. Tuthill, and T.R. Geballe, "Observations and modeling of the nonuniform dust outflow around the red supergiant NML Cygni," in *A Half Center of Stellar Pulsation Interpretations: A Tribute to A.N. Cox, ASP Conference Series* Vol. 135, eds. P.A. Bradley and J.A. Guzik, ASP Press, p. 329 (1998).

C. Townes, M. Bester, W. Danchi, D. Hale, E. Lipman, J. Monnier, and P. Tuthill, "Mid-infrared spatial interferometry on late-type stars and their circumstellar environments," *A Half Center of Stellar Pulsation Interpretations: A Tribute to A.N. Cox, ASP Conference Series* Vol. 135, eds. P.A. Bradley and J.A. Guzik, ASP Press, p. 316 (1998).

W.C. Danchi, P.G. Tuthill, M. Bester, E.A. Lipman, J.M. Monnier, and C.H. Townes, "IR imaging of circumstellar environments," in *Cool Star 10, ASP Conference Proceedings*, eds. Bob Donahue and Jay Bookbinder (1998).

C.H. Townes, M. Bester, W.C. Danchi, D.D.S. Hale, J.D. Monnier, E.A.Lipman, P.G. Tuthill, M.A. Johnson, and D. Walters, "Infrared Spatial Interferometer," *Astronomical Interferometry*, Robert D. Reasenberg, (ed.), *SPIE Proceedings* **3350**, 908 (1998).

E.A Lipman, M. Bester, W.C. Danchi, C.H. Townes, "Near-infrared guiding and tip-tilt correction for the UC Berkeley Infrared Spatial Interferometer," *Astronomical Interferometry*, Robert D. Reasenberg, (ed.), *SPIE Proceedings* **3350**, 933 (1998).

P.G. Tuthill, J. Monnier, W.C. Danchi, "Diffraction-limited Infrared Imaging of M-Giants at Keck," in *Cool Star 10, ASP Conference Proceedings,* eds. Bob Donahue and Jay Bookbinder (1998).

P.G. Tuthill, J.D. Monnier, W.C. Danchi, and C.A. Haniff, "Michelson Interferometry with Keck 1," in *Astronomical Interferometry,* Robert D. Reasenberg, (ed.), *SPIE Proceedings* **3350**, 839 (1998).

Figure 1

Visibility curves for the star NMLCygni at two different time periods separated by about 4 years. The difference between the two curves allows a measurement of the motion of material away from the star and also the distance to the star. Note the improvement in precision of measurement between 1994 and 1998.

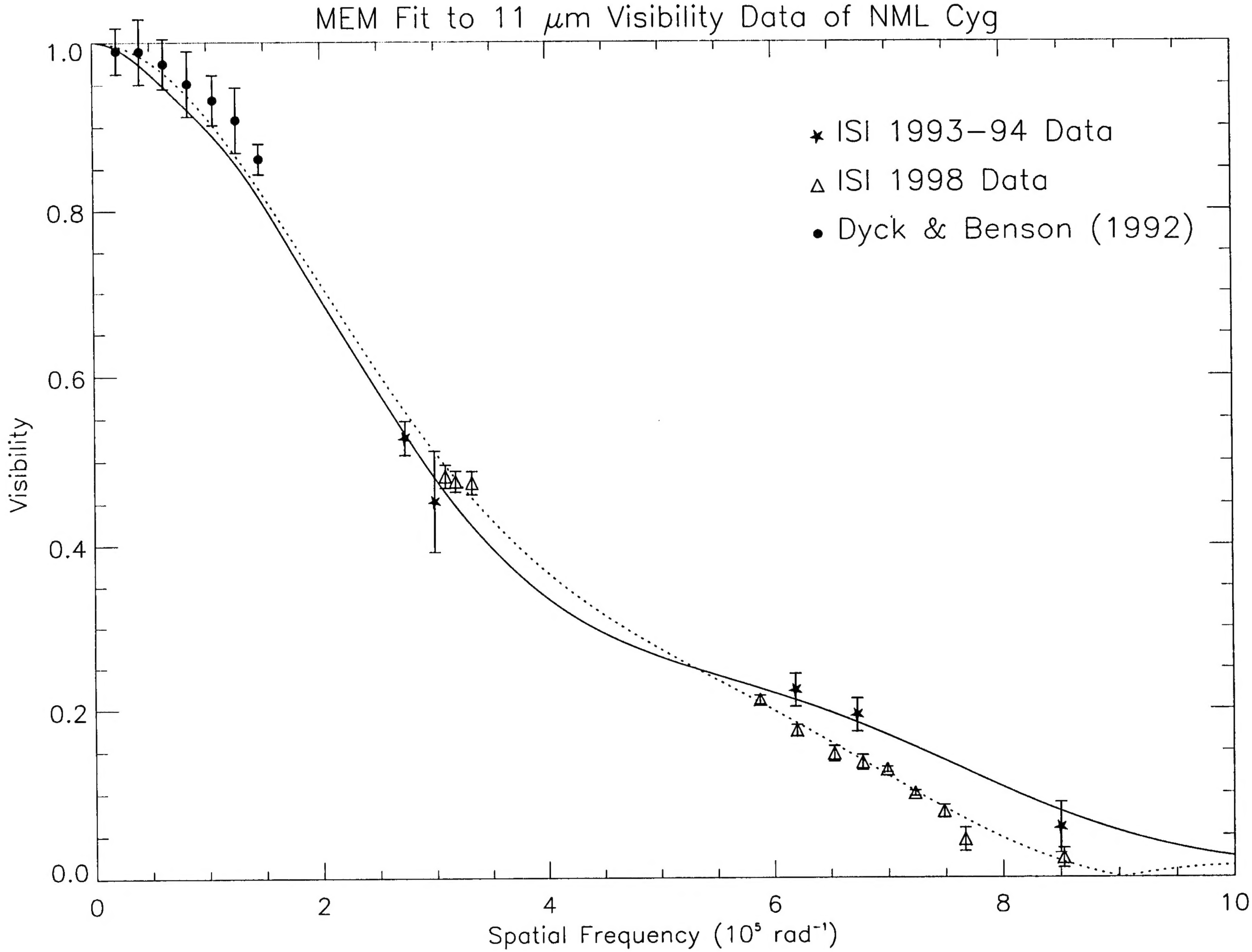
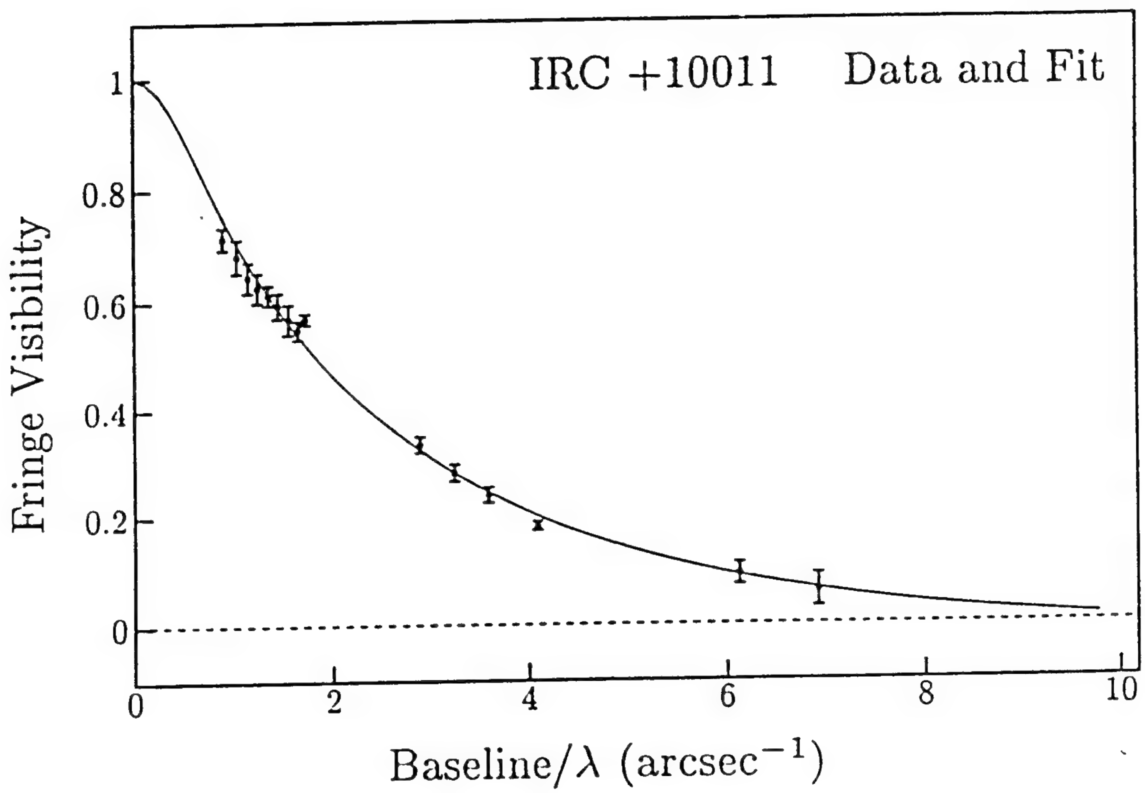

MEM Fit to 11 μm Visibility Data of NML Cyg
ISI 1993–94 Data
ISI 1998 Data
Dyck & Benson (1992)
Visibility
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
Spatial Frequency (10⁵ rad⁻¹)

Figure 2

The visibility curve of a newly measured star, IRC+10011. This new measurement was made possible by the recently installed new tracking cameras.

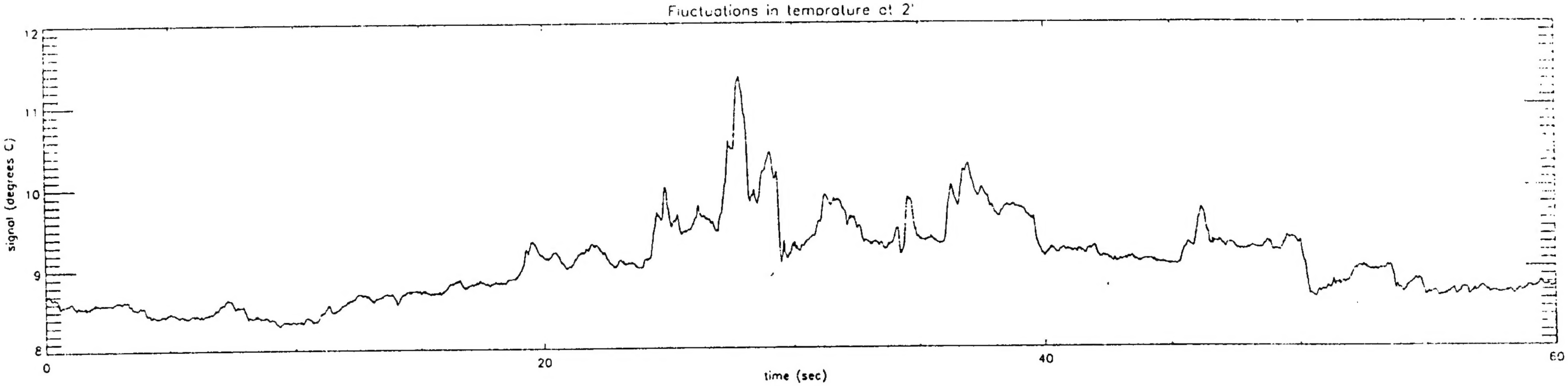


IRC +10011 Data and Fit
Fringe Visibility
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
Baseline/λ (arcsec⁻¹)

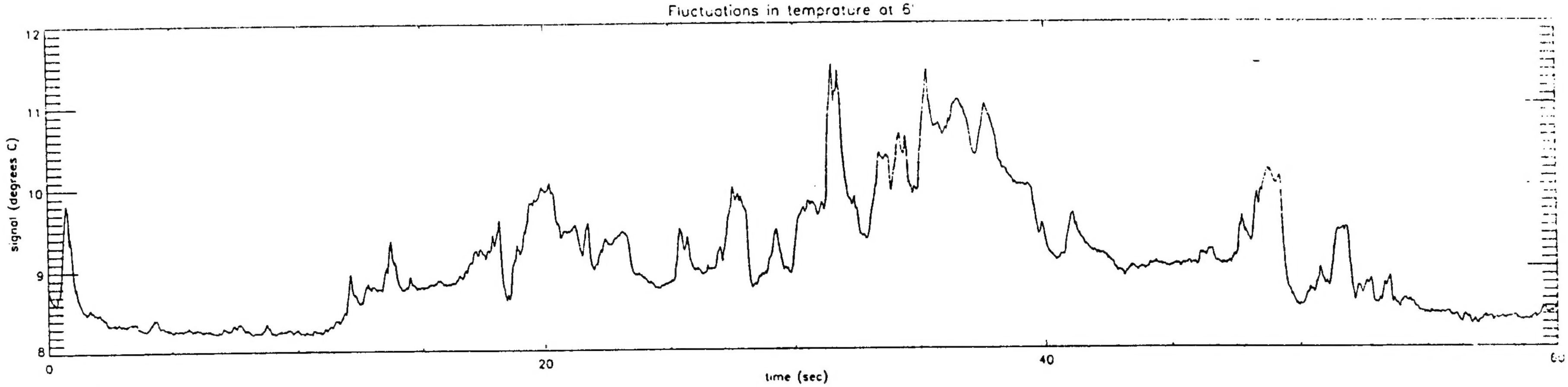
Figure 3

Demonstration of temperature fluctuation measurements in air at three nearby points. They have vertical heights of 2, 4, and 10 feet and were exposed to a wind of about 1 ft. per second. The magnitude of fluctuations is properly shown by the vertical scale, but absolute values were about 10° higher than those indicated. It can be seen that the slower fluctuations are fairly well correlated, but the faster ones are less correlated. These faster fluctuations extend a much shorter distance than do the slow ones, and hence do not affect the phase of light transmission as much. The data were taken near a building to test the functioning of fast, accurate, and local temperature measurements. They are not typical of a good 'seeing' or astronomical site.

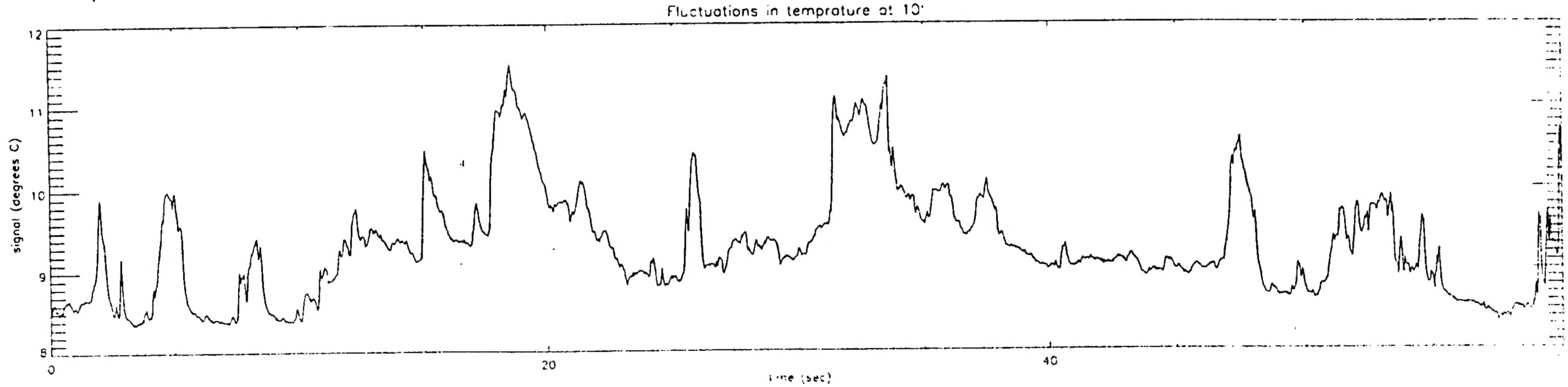
Fluctuations in temprature at 2'



Fluctuations in temprature at 6'



Fluctuations in temprature at 10'



Appendix I

Effects and detectability of scattered LO power which produces false IR signals in heterodyne detection, and its compensation.

Electron noise fluctuations in heterodyne detection are equivalent to an input noise power $h\upsilon$/sec per unit bandwidth per polarization. This corresponds to a noise power at 10 μm wavelength of $h\upsilon = 6.6 \times 10^{-27} \times 3 \times 10^{13} \times 10^{-7} = 2 \times 10^{-20}$ watts, or 4×10^{6} Jy allowing for the two polarizations which are assumed for calculating Janskys. This is equivalent to a single polarization wave of intensity E_n mixing with the local oscillator wave E_{LO} with $E_n^2 = 2 \times 10^6\ Jy$, where E is measured in appropriate units to make E^2 = Power in Janskys.

The detector current I is proportional to

$$\sum_{w_n} (E_{LO} \cos w_{LO}t + E_n \cos w_n t)^2 = \sum_{w_n} E_{LO}^2 \cos^2 w_{Lo} + 2E_{LO}E_n \cos w_{LO}t \cos w_n t$$

where the sum is over the noise band width. For simplicity, assume a detector quantum efficiency of unity. Results discussed here will be only approximate. If only frequencies below 10^{10} Hz are detected, then frequencies of $w_{LO} + w_n$ can be neglected, and

$$I = \sum_{w_n} \frac{E_{LO}^2}{2} + E_{LO}E_n \cos(w_{LO} - w_n)t$$

After rectification, the averaged noise power is proportional to I^2, and hence can be written, with appropriate scaling,

$$P_n = \sum_{w_n} \frac{E_{LO}^2 E_n^2}{2},$$

which is the noise power for 4×10^6Jy input.

Assume that, due to scattered LO radiation, a small additional signal is added of the same frequency as the local oscillator and of amplitude εE_{LO}. The noise power is then

$$P_n = \sum_{w_n} \frac{E_{LO}^2 E_n^2}{2} + \varepsilon\, E_{LO}^2 E_n^2 \,.$$

If this wave of intensity $\varepsilon\, E_{LO}$ is chopped, it will give a signal eqivalent to $\varepsilon\, E_{LO}^2 E_n^2$, or to $2\varepsilon \times 4 \times 10^6$ Jy. For this signal to interfere badly with stellar signals, it need not be larger than 800 Jy, or hence ε need not be larger than $\frac{1}{10^4}$.

The actual power in this small synchronous signal is only $\varepsilon^2 E_{LO}^2$, or 10^{-8} times the local oscillator power. This is the nature of the problem due to small amounts of back-scattered LO power, and makes it difficult to adequately eliminate the scattered LO power.

The detector current associated with this small chopped wave is

$\left(E_{LO}\cos w_{LO}t + \varepsilon\, E_{LO}\cos w_{LO}t\right)^2 - \left(E_{LO}\cos w_{LO}t\right)^2 = 2\varepsilon\, E_{LO}^2 \cos^2 w_{LO}t,$ which has an average value of $\varepsilon\, E_{LO}^2$, or 10^{-4} of the average detector current.

Similarly, the fluctuating current due to a signal wave $E_s \cos w_s t$ is

$\sum_{w_s}(E_{LO}\cos w_{LO}t + E_s \cos w_s t)^2 - (E_{LO}\cos w_{LO}t)^2$. When averaged, this is $\sum_{w_s} E_s^2$, where the sum is over the band width. For the signal wave to correspond to 800 Jy,

$\sum_{w_s} E_s^2 = 2\times 10^{-4}\sum_{w_s} E_n^2 = 2\times 10^{-4}\, E_n^2 \Delta w$ where Δw is the bandwidth. The ratio of this current to that due to the $\varepsilon\, E_{LO}$ signal is

$$\frac{E_s^2 \Delta w}{\varepsilon\, E_{LO}^2} = \frac{2\times 10^{-4}\, E_n^2 \Delta w}{\varepsilon\, E_{LO}^2} = \frac{2E_n^2 \Delta w}{E_{LO}^2}$$

$2E_n^2 \Delta w$ represents twice the total signal power, which for 800 Janskys = $6 \times 10^9 \times 800 \times 10^{-26} = 4.8 \times 10^{-14}$watts. This is very much smaller than the local oscillator power E_{LO}^2, which is $\sim 10^{-3}$ watts. Hence

the ratio of current modulation due to the chopped signal compared to that due to the back-scattered LO signal is very small.

From the above, it is clearly quite feasible to measure the chopped LO stray power to reasonable precision by using a lockin amplifier on the detector current. This LO current is $\sim 10^{-3}$ amps, and flows through an external impedance of 20 ohms. Hence measuring it to an accuracy of one part in 10^6, or to about 1/100 microvolts, is practical with chopping and averaging. This corresponds to detecting any spurious signal as large as that due to 8 Jy of thermal radiation. Such a measurement, and correction of the normal IR signals of the ISI with it, does not decrease the magnitude of the actual stellar signal noticeably, but can eliminate most of the spurious signals due to LO scattering.